Compact and broadband circularly polarized ring antenna with wide beam-width for multiple global navigation satellite systems*

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A compact and broadband circularly polarized (CP) annular ring antenna with wide beam-width is proposed for multiple global navigation satellite systems (GNSS) in the L1 band. The annular ring is excited by two modified L-probes with quadrature phase difference. It has a 36.3% 10-dB return loss bandwidth and a 13% 3-dB axial ratio bandwidth, because of the orthogonal L-probes with 90° phase difference. The measured peak gain of the antenna is 3.9 dBic. It can detect the satellites at lower elevation as its half power beam-width (HPBW) is 113° in both the x–z and y–z planes, achieving a cross-polarization level of larger than 25 dB. Noticeably, the antenna achieves 89% size reduction compared with the conventional half wavelength patch antennas. It can be used in hand-held navigation devices of multiple GNSS such as COMPASS, Galileo, GPS and GLONASS.

Keywords: global navigation satellite system, annular ring antenna, circular polarization, wide beam-width

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1. Introduction

Currently, several countries or organizations are working on their own global navigation satellite systems (GNSS) to provide continuous and stable navigation services. However, systems under construction such as Chinese COMPASS and European Galileo have few operational satellites and may not be able to provide continuous and stable services to the users of the systems. To deal with this issue, antennas in hand-held navigation devices are required to have wide beam-width to capture as more satellites as possible. Moreover, if the antenna has broad bandwidth, it will give the devices the ability to switch to an alternative system when it is necessary. The circularly polarized (CP) antennas with dual or quad feeds in Refs. [1]–[9] have relatively broad axial ratio (AR) bandwidths so as to allow the antennas to operate in multiple GNSS. However, because of their half power beam-width (HPBW) (60°–90°), they are commonly used in GPS or GLONASS systems. 130°–190° of HPBW are achieved by either extending the substrate beyond the ground plane as in Ref. [10] or adopting pyramidal ground structure and a partially enclosed flat conducting wall as in Ref. [11]. Unfortunately, their AR bandwidths are about 1% which are not wide enough for multiple GNSS applications. In Ref. [12], the antenna has a broad AR bandwidth and a wide beam-width by integrating two bowtie patch antennas and two trapezoidal-shaped dipoles, but its size needs to be reduced to be used in hand-held navigation devices.

In this article a compact and broadband CP annular ring antenna with a wide beam-width is reported. The antenna is based on high permittivity ceramic substrate and excited by two modified L-probes with quadrature phase difference. The antenna's tested AR bandwidth (AR $\leq$ 3 dB) and return loss bandwidth ($|S_{11}| \leq -10$ dB) are 13% and 36.3%, respectively. The peak gain of the proposed antenna within the bandwidth is 3.9 dBic and the measured HPBW of the proposed antenna is 113° for both x–z and y–z planes. In addition, because of the ring structure and the high permittivity of its substrate, the antenna has achieved 89% size reduction in comparison to the conventional half-wavelength patch antennas. The proposed antenna can be used in COMPASS, GPS, Galileo and GLONASS compatible hand-held navigation devices

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operating in the L1 band.

2. Antenna design

The annular ring antenna is fed by two modified L-probes, as shown in Fig. 1. The two L-probes are connected to the output ports of the Wilkinson power divider printed on the lowest layer. The radiating annular ring patch and the power divider share the same ground plane in the middle. All the metal layers are printed on the dielectric surfaces, which leads to much easier fabrication process in mass production.

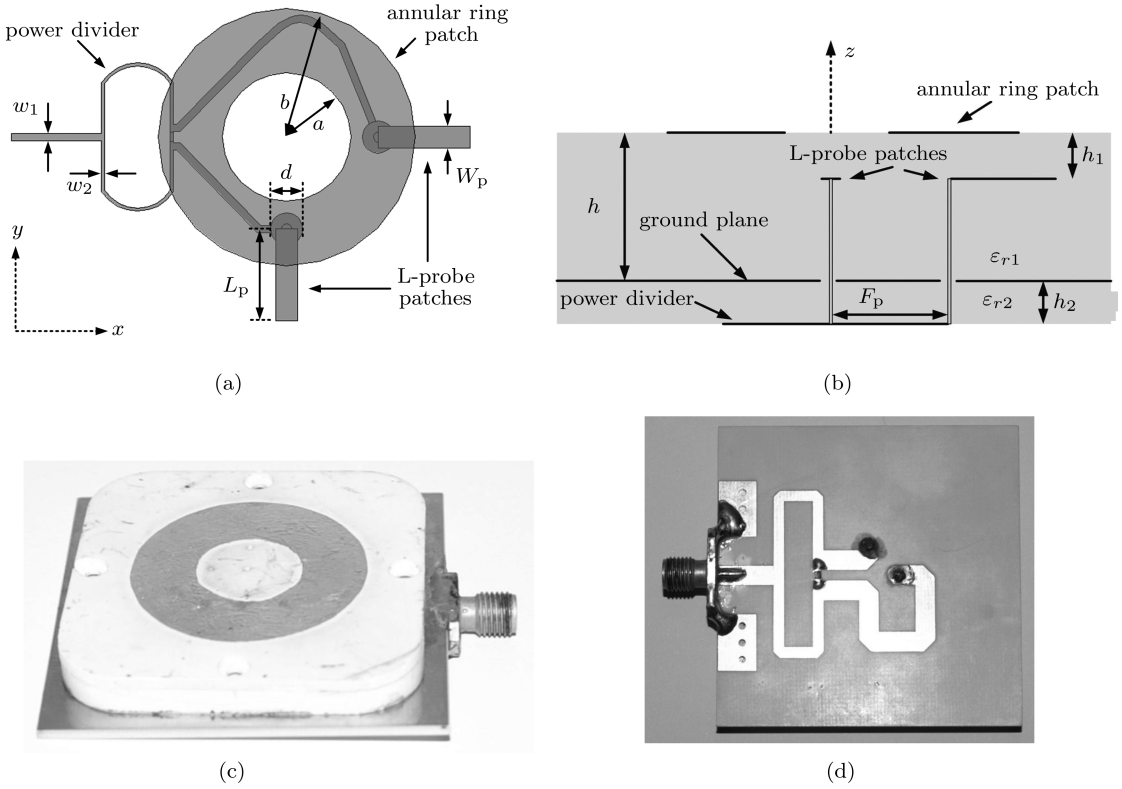


Fig. 1. Antenna structure: (a) top view of the proposed antenna, (b) side view of the proposed antenna, (c) photo of the antenna, (d) photo of power divider on the back of the antenna.

2.1. Radiating structure

To make sure the antenna has a small size and radiates maximally to the broadside direction, we choose an annular ring as the radiating body, as shown in Fig. 1. An annular ring antenna works at transverse magnetic (TM) modes when the height of the substrate is much thinner than the guided wavelength at the operating frequency. With reference to Refs. [13] and [14], the resonance of a coax fed annular ring antenna is determined by

$$f_{nm} = \frac{ck_{nm}}{2\pi\sqrt{\varepsilon_{\text{eff}}}}\,, \tag{1}$$

where c is the speed of light traveling in vacuo, ε_{eff} is the effective permittivity. And k_{nm} is the roots of the following equation

$$\mathrm{J}'_n(k_{nm}a)\mathrm{Y}'_n(k_{nm}b) - \mathrm{J}'_n(k_{nm}b)\mathrm{Y}'_n(k_{nm}a) = 0, \tag{2}$$

where a and b are the inner and outer radii of the annular ring; $\mathrm{J}_n(x)$ and $\mathrm{Y}_n(x)$ are Bessel functions of the first and second kind of order n respectively, the prime ($'$) denotes the first derivative.

From Eqs. (1) and (2), the antenna's size is determined by the average radius $(a+b)/2$ of the ring and by the relative permittivity of its substrate. Operating at 1.57 GHz, the ring parameters are set at $a = 7.45$ mm, $b = 14.9$ mm on a 6-mm thick substrate with $\varepsilon_r = 9.2$, with which the antenna is working at TM_{11} mode for $n = m = 1$. When working at this mode, the size of the ring is smaller than the rectangular and circular patches.[13,14]

2.2. Impedance matching and polarization configuration

The input impedance of annular ring antenna is very high when the annular ring works at the TM_{11} mode.[15,16] Two orthogonal-modified L-probes are placed beneath the ring patch to excite the annular ring and transform the input impedance of the ring to

lower values. The modified L-probes are constructed with two square metal strips and the two posts connected to the 90° power divider printed on the back side of the antenna. The dimensions of the two probes and the distances from the ring to the square strips affect the coupling between the ring patch and the probes.

To achieve broadband circular polarization, a 90° power divider is added on the back side of the antenna to achieve quadrature-phase feeding to the two modified L-probes. The power divider is grounded by a metal plane which is also the ground plane for the modified L-probe patches and the annular ring patch. Two holes of the same diameter d are etched out in the ground plane to let the two metal posts pass through. The divider is set to work at 1.57 GHz and the amplitudes of the two ports are the same. The amplitude and phase error curves of the scattering parameter of the power divider are obtained with Ansoft HFSS 10 and plotted in Fig. 2. It can be seen that the amplitude of the two output ports are in good balance and the phase difference error is less than 5° over 1.48 GHz–1.65 GHz. The power divider is implemented on a substrate of 1.524-mm height and its relative permittivity is 3.55.

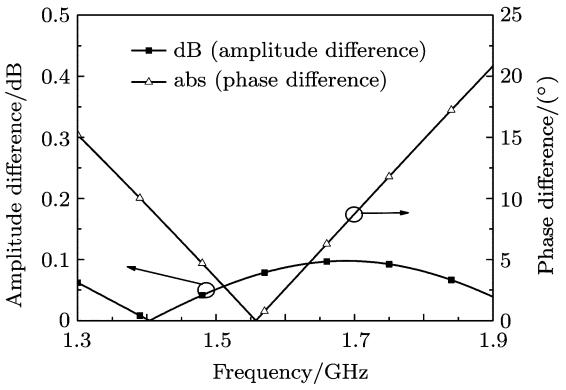


Fig. 2. Amplitude and phase errors of the power divider.

According to Ref. [17], circular polarization level of a dual-feed CP antenna is determined by

$$\mathrm{AR_{dB}} = \sqrt{A_\mathrm{e}^2 + 0.0225(\phi_\mathrm{e} + \beta_\mathrm{e})^2}\,, \qquad (3)$$

where A_e is the amplitude difference in dB of the two feeds; ϕ_e is the phase difference error of the two feeds in degrees; and β_e is the orthogonality error of the two L-probe patches in degrees. In this design, the two modified L-probes are placed orthogonally and this makes β_e to be zero. So the amplitude and phase difference error determine the AR of the annular ring antenna. The calculated AR is only 0.1 dB at the operating frequency.

2.3. HPBW study

The HPBW of the antenna is related to the permittivity of the substrate and the size of the radiator. To reveal the relation between the HPBW and the permittivity of the substrate, four annular ring antennas are simulated. The four antennas are all operating at 1.57 GHz and have the same height of 6 mm. To reduce ground size effects, the grounds and substrates are chosen to be much larger than the ring patches. The results and substrate/ground parameters of the four antennas are tabulated in Table 1.

Table 1. Gain and HPBW comparison for different substrate permittivities.

Antenna No.	Permittivity ε_r	Ground size /mm	Directivity /dBic	HPBW /(°)
1	1	146 × 146	9.2	64
2	2.2	106 × 106	7.5	78
3	4.4	78 × 78	6	95
4	9.2	52 × 52	4.5	110

Regarding Table 1, the HPBW of the antenna changes from 64° to 110° when the permittivity changes from 1 to 9.2. It is also noted that the directivity of the antenna declines from 9.2 to 4.5 because of the permittivity change.

3. Results and discussions

By using Ansoft's full wave tool HFSS 10, the dimensional parameters for the antenna are chosen to be $a = 7.45$, $b = 14.9$, $w_1 = 3.38$, $w_2 = 1.85$, $L_p = 9.7$, $W_p = 1.8$, $d = 1.75$, $h = 6$, $h_1 = 2$, $h_2 = 1.524$, $F_P = 10$. All dimensions are in millimeters. The ring substrate size is 48 mm by 48 mm and the ground plane is 52 mm by 52 mm. The substrate for the ring and the L-probes is ceramic and its relative permittivity (ε_{r1}) is 9.2. The total height of the ceramic substrate is 6 mm. The power divider for the antenna is fabricated on a substrate with the relative permittivity of 3.55 and its height is 1.524 mm.

The variations of impedance of the ring antenna fed by a coaxial probe and L-probes are given in Fig. 3. It shows that utilizing L-probes instead of coax probes to excite the ring patch will not affect the resonance. Moreover, the high antenna impedance is transformed by replacing the coax probe with L-probe to excite the antenna.

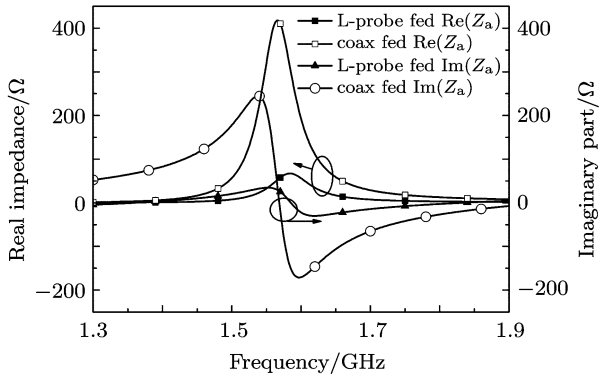


Fig. 3. Annular ring antenna impedance curves, directly fed by a coax probe and by a modified L-probe.

Figure 4 plots the simulated and tested magnitudes of S_{11} of the prototype antenna. It shows that the measured return loss bandwidth of the antenna varies from 1.24 GHz to 1.81 GHz, which is benefitted from the modified L-probes and the 90° power divider on the back of the antenna. The 90° power divider also acts as a matching circuit between the annular ring and its load.

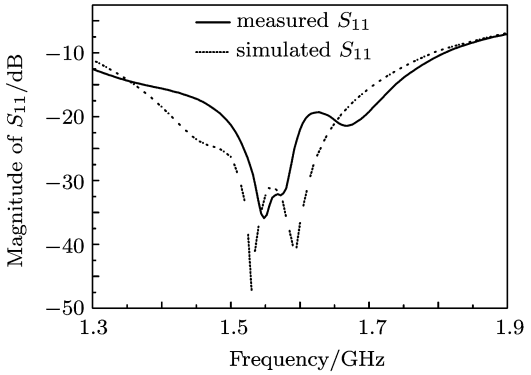


Fig. 4. Simulated and measured magnitudes of S_{11} of the proposed antenna.

Figure 5 shows the simulated and measured axial ratio and gain of the prototype antenna. It is found that the measured axial ratio bandwidth (AR $\leq$ 3 dB) of the antenna is over 200 MHz from 1.46 GHz–1.66 GHz, which is sufficiently wide for the GNSS operating around 1.57 GHz. The broad AR bandwidth is achieved owing to the orthogonal-modified L-probes and the 90° power divider. Figure 5 also shows that the measured gain is larger than 2.5 dBic from 1.56 GHz–1.62 GHz, which includes the operation frequencies of COMPASS, GPS, Galileo, and GLONASS in the L1 band.

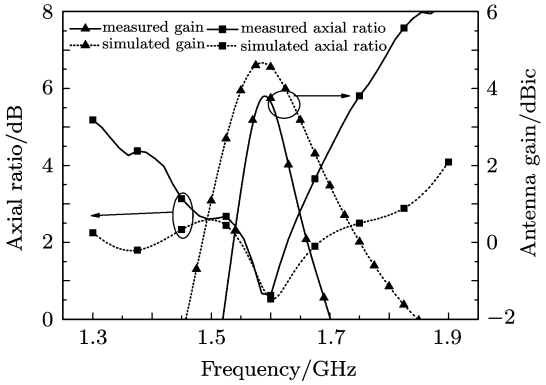


Fig. 5. Measured axial ratio and gain of the proposed antenna.

The simulated and measured patterns of the antenna in x–z and y–z planes are given in Fig. 6. Because the antenna is symmetrical, the patterns in the two planes are nearly the same. The cross polarization level at 1.575 GHz is over 25 dB in the broadside direction. The half power beam-widths are 113° for both the planes.

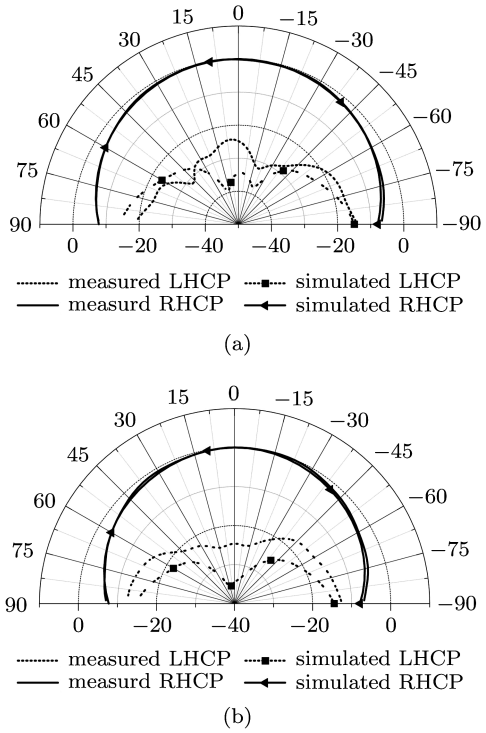


Fig. 6. Measured radiation patterns of the proposed antenna: (a) f = 1.575 GHz in x–z plane and (b) f = 1.575 GHz in y–z plane.

It is noted that there are some discrepancies between the simulated and measured results in Figs. 4, 5 and 6, which are caused by the ceramic substrate shrinkage at high temperatures during the fabrication process.

Table 2. Comparison of measured gain and HPBW between the proposed antenna and reference antennas.

Antenna	Dimensions/mm	Permittivity (ε_r)	AR bandwidth/%	Gain/dBic	HPBW/(°)
Ref. [3]	180×180×20	1	64	8	64
Ref. [10]	120×120×3.2	9.5	0.62/0.69	4.1/3.2	126/190
Ref. [11]	150×150×22	4.4	0.76	-0.6	131
Ref. [12]	200×200×38	1	33	6.6	106
This work	48×48×7.52	9.2	13	3.9	113

Table 2 compares some test results and dimensional parameters between the proposed and reference antennas. It shows that the proposed antenna has the smallest size but it offers good AR bandwidth, gain and HPBW. The proposed antenna has a tested AR bandwidth of 13%, HPBW of 113° and peak antenna gain of 3.9 dBic.

4. Conclusion

A compact and broadband CP annular ring antenna is reported. Broadband circular polarization has been achieved by exciting the annular ring patch with two orthogonal L-probes with quadrature-phase difference. The measured return loss and axial ratio bandwidths are 13% and 36.3%, respectively. The measured peak gain of the antenna is 3.9 dBic and the gain of the antenna is greater than 2.5 dBi in the frequency range of 1.56 GHz–1.62 GHz. The proposed antenna has 113° HPBW in both the x–z and y–z planes, which enables the antenna to capture satellites at a large elevation angle in GNSS under constructions such as COMPASS and Galileo. Moreover, the antenna has achieved 89% size reduction, compared with the conventional half wavelength patch antennas. The antenna can work efficiently at COMPASSS B-1/B1-2, Galileo E1/E2, GPS L1, and GLONASS L1 frequencies.

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